The Effects of Electron Collisions with Atmospheric Neon.

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The present paper contains an account of an investigation of the effects of electron collisions with neon atoms by a method similar to that used with helium and with argon. The apparatus employed* is practically the same as that described in the account of the experiments with argon,† the only difference being that one of the lower gauzes (C) was removed and that two small platinum plate electrodes were sealed into the ionisation chamber, so as to provide an electric field at right angles to the direction of the electron stream. The arrangement will be understood by reference to fig. 1, in which the lettering corresponds to that used in the earlier paper. The object of introducing the side electrodes, G and H, was to enable a second test of the production of ionisation to be made by means of a delicate galvanometer included in a subsidiary circuit.

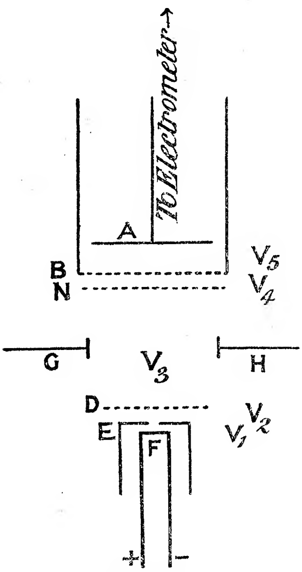

FIG 1

The usual precautions for ridding the glass and the electrodes from occluded gases were taken, and in all the observations recorded in the paper a magnetic field parallel to the axis of the discharge tube was used to prevent the electron stream from spreading laterally.

The neon used was supplied to us by Dr. F. W. Aston, who had purified it by the method of repeated fractionation (over charcoal cooled in liquid air), using the apparatus he has described in the 'Philosophical Magazine,' vol. 37, p. 527 (1919). The process was repeated many times after the stage had been reached when the density of the gas was unchanged by further fractionation. The authors gladly take this opportunity of expressing their

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† 'Roy. Soc. Proc.,' A, vol. 97, p. 1 (1920).

thanks to Dr. Aston for providing them with a sample of his purest neon. The gas was stored in a glass globe with a good stopcock, which led into a fine capillary tube, through which it passed into the apparatus, entering by way of a U-tube containing a little carbon and immersed in liquid air, this arrangement being similar to that described in the account of our experiments with helium, except for the smaller quantity of carbon employed. During the course of the research the spectrum of the neon was examined in the apparatus by means of a Hilger direct wave-length spectroscope, the luminosity being produced by the electron stream from the glowing filament, and only known neon lines were seen. The spectroscopic test is, however, not so good a guarantee of the absence of impurities as the density observations of Dr. Aston.

Preliminary Experiments.

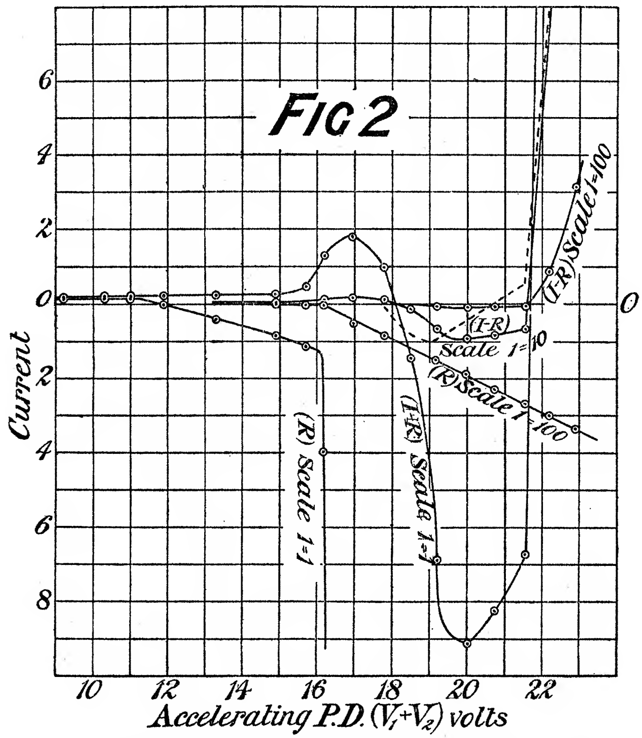
For the general investigation of the effects of electron collisions with neon atoms, and for the determination of the approximate values of the critical velocities for electrons in this gas, the various electric fields were so arranged that when a critical velocity was reached the electrons should be able to make collisions over a considerable distance before their velocity was reduced below the critical value. This condition was secured by having the gauze D and N at the same potential, and by turning back the electrons in the space between the gauzes B and N. The immediate production, throughout the whole of the ionisation space, of radiation or ionisation, as the case might be, when a critical velocity is reached, is thus made possible, and the chances of detecting the radiation or ionisation as soon as it is produced are increased.

In all the preliminary experiments the electrons were accelerated up to the gauze D by the fields V_1 and V_2, of which V_1 had the constant value 7 volts, while the variation of the speed of the electrons entering the space between the gauzes D and N was affected by the gradual increase of the potential difference applied between E and D. Of the two side electrodes, G and H, one, G, was maintained at the same potential as the gauzes D and N, while the other side electrode, H, was either maintained at a potential of -3 volts with respect to G, or was kept at the same potential as G, according as it seemed desirable or not to restrict the number of positive ions reaching the collecting electrode. The electrons in the stream from the filament were prevented from reaching the plate A by the opposing potential difference applied between B and N, which was sufficiently great to turn them back to the gauze N. The electrometer should therefore give no indication of a current until the velocity of the electrons is such that their collisions with gas atoms give rise to either radiation or ionisation. When radiation is

produced in the gas, the resulting photo-electric current will be positive or negative according as the plate A is negative or positive with respect to the gauze B. When ionisation is produced in the gas, its detection depends upon the diffusion of the positive ions from the space between the gauzes D and N into the space between the gauzes N and B, where they are accelerated towards the plate A by the potential difference, V_4, which retards the electron stream. If the gauze B is at a positive potential with respect to the plate A, positive ions will be further accelerated towards the collecting electrode. In this case the photo-electric effect of the radiation acting on the plate A gives a positive current, so that both radiation and ionisation tend to give a current in the same direction, and for this reason curves taken with this arrangement of fields will be referred to as (I+R) curves. If the gauze B is at a negative potential with respect to the plate A, radiation will give a negative current, while the collection of positive ions produced by ionisation will depend upon whether the opposing potential difference, V_5, is sufficient to turn them back or not. Curves in which the positive ions are able to reach the collecting electrode in spite of an opposing field, V_5, will be referred to as (I−R) curves, since in this case the radiation current will be opposite in direction to the ionisation current. In curves of this type a positive or a negative current will be obtained according as the effect of ionisation or of radiation predominates. Series of observations in which the positive ions are prevented from reaching the collecting electrode by the opposing field, V_5, will be referred to as R curves, since in these circumstances the electrometer measures the radiation current alone.

Typical examples of (I−R) curves and R curves are given in fig. 2. These two series of observations were taken simultaneously, corresponding points on the two curves being taken consecutively. In this way the two series were obtained under identical conditions. The average pressure of neon in the apparatus during these experiments was 0·025 mm. The R curve, considered alone, shows that a negative current indicating radiation is first produced when the applied accelerating potential difference is about 11 volts, and that a sudden increase in the amount of radiation produced takes place when the applied potential difference is increased to about 16 volts. In the (I−R) curve, the effect of the radiation, which the R curve indicates as being produced when the accelerating potential difference has a value of about 11 volts, is obscured by the secondary effects of the bombardment of the gauze N by the electron stream. This curve, however, shows that a positive current, increasing with (V_1+V_2), begins when this potential difference has a value of about 15 volts. The curve begins to turn down when (V_1+V_2) is between 16 volts and 17 volts, the positive current decreasing, and an

increasing negative current being obtained. This negative current continues to increase until the accelerating potential difference reaches a value between 19 volts and 20 volts, after which it gradually decreases. Another bend in



The broken (I-R) curve, scale 1-10, represents observations with decreasing values of (V_1+V_2).

the curve is obtained when the applied accelerating potential difference is increased to about 21·5 volts, after which the curve slopes up at a greatly increased rate, indicating a rapidly increasing positive current. Considering the (I—R) curves and the R curves together, it will be observed that, at the three stages at which the (I—R) curves turn towards the positive direction, namely, about 15 volts, between 19 volts and 20 volts, and between 21 volts and 22 volts, the R curve shows no change of slope. The three stages mentioned may therefore be taken as giving indications of the increased production of ionisation rather than a reduction in the amount of radiation produced. As a result of the preliminary experiments, of which these curves are typical, it was decided to investigate the following points in greater detail:—

1. The production of radiation at an applied potential difference of about 11 volts.

2. The increased production of radiation at an applied potential difference of between 16 volts and 17 volts.

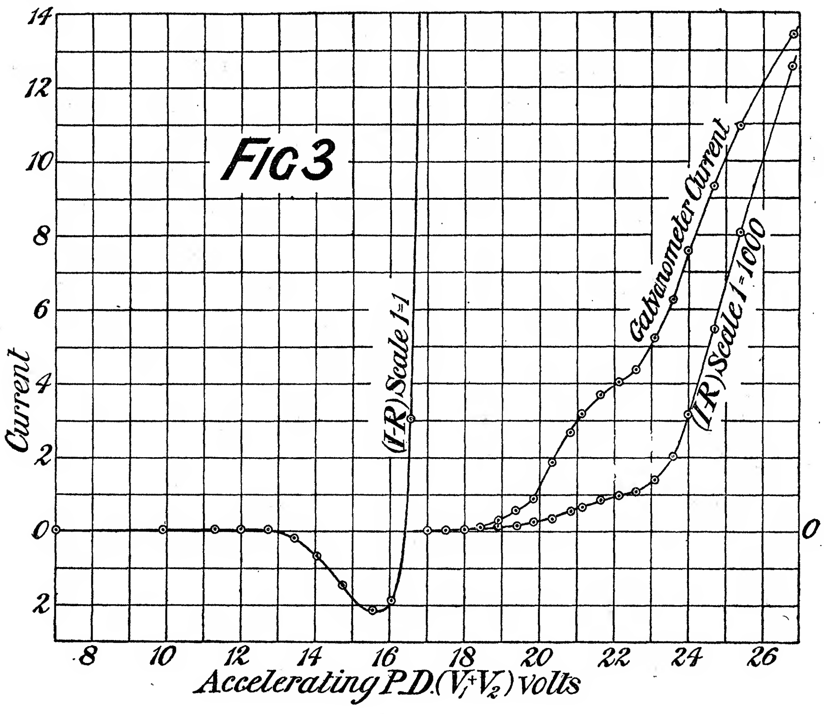
3. The production of ionisation at an applied potential difference of about 15 volts.

4. The increased production of ionisation at an applied potential difference of between 19 volts and 20 volts.

5. The further increased production of ionisation at an applied potential difference of between 21 volts and 22 volts.

Before passing on to the more detailed investigation, it must be mentioned, in connection with the preliminary experiments, that, in some cases, another type of (I—R) curve was obtained. While, in every case investigated, the R curve gave an indication of the increased production of radiation at an applied potential difference of between 16 volts and 17 volts, some instances of (I—R) curves were obtained where no indication of this second type of radiation was shown, but where the positive current increased steadily from an applied potential difference of 15 volts until one of the higher ionisation velocities was reached. In these cases, it is clear that the ionisation of the type produced at an applied potential difference of 15 volts must have been considerably in excess of the radiation of the type produced at an applied potential difference of between 16 volts and 17 volts. The occurrence of these two types of (I—R) curves suggests that the ionisation and radiation concerned are to be attributed to different kinds of atomic systems. Curves showing two radiation velocities were usually obtained when neon at a low pressure was streaming through the apparatus immediately after it had been highly evacuated and the carbon purifying tube had been heated to drive out the occluded gas, while, in general, curves of the second type were obtained with gas that had been present in the apparatus a longer time. (I—R) curves of the first type could sometimes be obtained by the use of a very small electron stream under conditions when the employment of a larger electron stream gave (I—R) curves of the second type. An illustration of an (I—R) curve of this type is given on two scales in fig. 3. During the series of observations represented in this figure, the gauzes N and D were at the same potential, but the side electrode, G, was at a negative potential of 5·6 volts with respect to the negative end of the filament. The other side electrode, H, was at a negative potential of 17 volts with respect to G, and the circuit between these two electrodes included a galvanometer. As both the side electrodes were negatively charged with respect to the gauze D, the maximum velocity the electrons acquire is that with which they pass through this gauze. With the arrangement of electric fields indicated, the current measured by the galvanometer was that due to ionisation alone

since the side electrodes were too small for the radiation to cause a photo-electric current measurable on the galvanometer. By comparing the electrometer and galvanometer current curves in fig. 3, it will be observed that, when ionisation was first detected by the electrometer, the amount of ionisation produced was too small to give an indication on the galvanometer. Though the beginning of ionisation was not detected by the galvanometer, this instrument gave clear indications of the increased production of ionisation at an applied potential difference of between 19·5 volts and 20 volts, and again between 22 volts and 23 volts.



In some instances, the investigation was complicated by the sudden occurrence of a large increase in current, which was detected simultaneously in both R and (I—R) series of observations. The increase of current observed in the (I—R) series was an increase of positive, or ionisation current. This is similar to an effect recorded in the account of our experiments with argon. The increase was most marked in cases where a large electron emission was used, and when the gauzes N and D were at the same potential. It did not always occur for the same value of the applied accelerating potential difference, but in no instance was it obtained for a value of this potential difference less than about 16 volts. In the case of

argon, this phenomenon was attributed to an enormously increased effective emission resulting from the neutralisation of the space charge effect by positive ions travelling down to the filament. In the case of neon, it was found that the effect was not obtained when the fields were so arranged that positive ions could not readily pass down to the filament, a fact which supports the explanation suggested. Attempts to detect directly an increase in the effective emission from the filament were, however, not successful.

The Exact Determination of the Critical Velocities.

The critical points found in the experiments described in the earlier section of the paper have been referred to the values of the applied accelerating potential difference at which the effects are indicated in the curves. In attempting to determine accurately the value of the minimum electron velocity at which any given effect could first be obtained, it is necessary to make a correction to the observed accelerating potential difference to allow for the velocity of emission from the filament of the electrons which produce the effect. In previous communications the authors have based their determination of the magnitude of the correction to be applied in any given instance upon the assumption that the number of electrons present in the stream from the filament, having the velocity of the swiftest that could be detected, was sufficient to give a detectable amount of radiation or of ionisation when a critical point was reached. The correction was found by determining the value of the retarding potential difference which had to be applied in order to prevent electrons from the filament, accelerated by a given potential difference, from reaching the collecting electrode in sufficient quantity to be detected by the electrometer, and by taking the difference between the applied retarding and accelerating potential differences, when this stage had been reached, as the correction. It was realised that the values of critical velocities deduced in this way might be rather higher than the true values, but the results obtained for certain critical points by methods which yielded values free from the necessity for correction tended to confirm the values which were dependent upon the application of a correction, and showed that in these cases the error involved in taking as the value of the critical velocity that of the swiftest electrons present when a critical stage was reached, could not be serious.

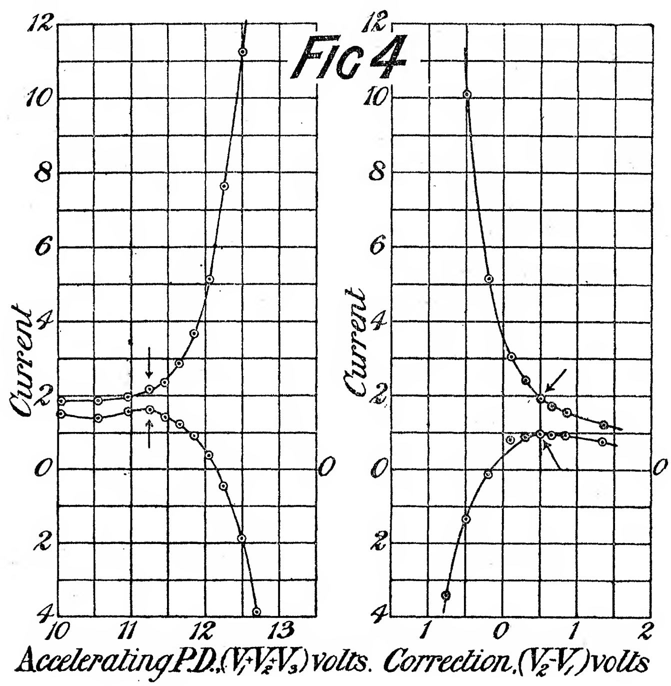
In the present investigation considerable ranges of pressures and intensities of electron stream were employed in different series of observations, and it was found that the values of the correction varied over a wider range than the corresponding applied potential differences at which the effects were observed in the curves. This was particularly noticeable in the case of the first

radiation point. It was, therefore, clear that with the form of apparatus and the arrangement of fields employed in this investigation an error was involved in taking the correction from the swiftest electrons present. The correction to be applied to any given critical stage was therefore determined by ascertaining the highest value of the retarding potential difference which could be applied to allow electrons from the filament, accelerated by a given potential difference, to get through against the retarding field in sufficient quantity for them to produce a detectable amount of radiation or of ionisation under conditions as nearly as possible the same as those employed in the actual experiment. This was done by giving the field V_1, between the filament and E, a constant value—about 5·8 volts in most of these experiments—and by applying between E and D a retarding potential difference by the variation of which the number of electrons getting through into the space between D and N could be controlled. Between D and N a constant accelerating potential difference was applied, the value of which was fixed a little above the value found for the critical velocity for which the correction was under investigation, this velocity having been deduced in the manner of our earlier researches. This ensured that *all* the electrons passing into the space between the gauzes D and N against the opposing potential difference V_2 would be able to acquire the critical velocity in question. The two side electrodes were maintained at the same potential as the gauze D. Between the gauzes N and B a constant retarding potential difference was applied, sufficient to prevent any of the original electrons reaching the collecting electrode. The final potential difference between the gauze B and the plate A was fixed according as it was desired to detect the effect in question in an $(I+R)$, an $(I-R)$, or an R curve. The retarding potential difference V_2, which controlled the number of electrons used, was then varied until the electrometer first indicated a radiation or an ionisation current, as the case might be. When this stage is reached, it is clear that the number of electrons passing through into the space between D and N is the minimum number required to give a detectable effect (of the type under investigation) with the special arrangement of fields used. The $(I-R)$ or R curve from which a value of a critical point is to be deduced must be taken with as nearly as possible the same arrangement of fields as that employed in estimating the correction, and in this case it is clear that the correction to be added to the observed value must be the difference between the potential differences V_2 and V_1, when V_2 is adjusted to give the minimum number of electrons necessary for the effect to give a detectable current. It was found that the corrected values of critical velocities, determined in this way, showed very little, if any, variation when deduced from series of observations taken

with intensities of electron stream and gas pressures which varied over a considerable range from series to series.

The Minimum Radiation Velocity.

In order to be able to apply the correction found in the manner described above to obtain a value of a critical velocity from a series of observations of the variation of current with increasing accelerating potential difference, it was necessary that the series of observations should be taken with the variable part of the accelerating potential difference applied between the gauzes D and N, the fields V_1 and V_2 being constant accelerating fields. Therefore, in all the curves from which accurate values of critical velocities have been deduced, it was not possible to maintain the gauzes D and N at the same potential and to allow the radiation or ionisation to be produced throughout the whole space at once, as in the preliminary experiments. The series from which accurate values of the first radiation velocity were deduced were of two types. In one type the radiation current was examined alone in an R series, the correction being also deduced from observations with the field V_5 arranged for an R curve. In the second type (I−R) and (I+R) series of observations were taken simultaneously, corresponding points on the two curves being taken consecutively. The point of divergence of these two



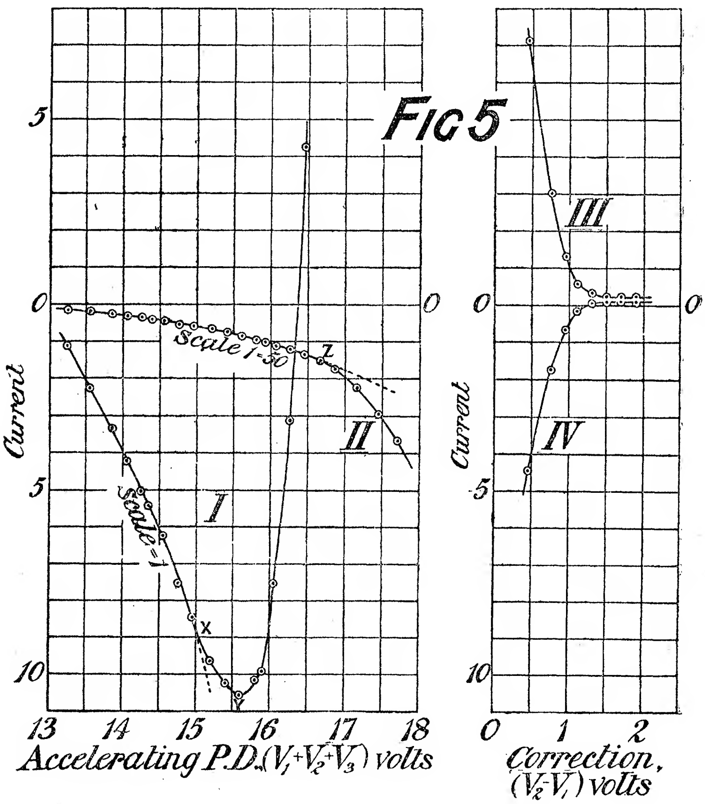
curves was taken as indicating the beginning of radiation. In obtaining the correction for this type of series (I+R) and (I−R) sets of observations were also taken simultaneously for different values of V_2, and the value of V_2 at which these began to diverge was used for deducing the correction. The corrected values of the minimum radiation velocity, obtained by the two methods, varied between 11·75 volts and 11·95 volts. The mean of all the results—11·8 volts—was therefore taken as the value of the first radiation velocity. An example of (I−R) and (I+R) series, with the corresponding curves for the correction, from which a value was deduced, is given in fig. 4. These curves were taken with neon at an average pressure of 0·133 mm. in the apparatus.

The Minimum Ionisation Velocity.

The type of curve from which it was found that values of the minimum ionisation potential difference could be obtained most satisfactorily was the (I−R) curve. This involved the detection of the beginning of ionisation in the presence of the negative current due to radiation of the first type. The ionisation current always increased much more rapidly with increasing electron velocity than the current due to the first radiation, so that it was possible to adjust the temperature of the filament so that the radiation current should be quite small and almost negligible without also reducing the ionisation current to the stage when it would be difficult to detect its beginning. In cases where a very small electron stream was employed and the current due to the first radiation was negligible, the detection of the beginning of ionisation depended upon the first indication of an increasing positive current. Where the negative current due to radiation was not negligible, the detection of the beginning of ionisation depended upon the determination of the first point at which the rate of increase of the negative current showed signs of diminishing. Series of observations were taken at average pressures, ranging from 0·006 mm. to 0·310 mm., and for several different values of the intensity of the electron stream.

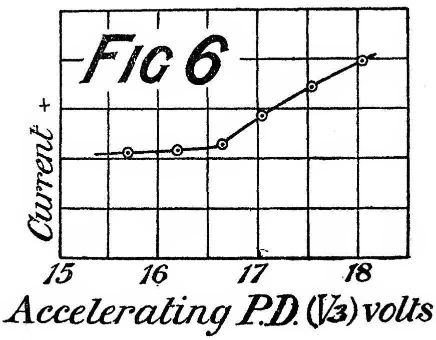
In determining the correction (to be applied in order to obtain the minimum ionisation velocity), the arrangement of the fields V_4 and V_5 had to be that required for an (I−R) series. It was anticipated that there might be some difficulty in estimating this correction, owing to the possibility that, when V_3 had been adjusted to a value just sufficiently great to ensure that all the electrons should be *able* to acquire the velocity necessary for the first ionisation, some of the electrons getting into the space between the gauzes D and N might produce radiation of the first type instead of ionisation. Collisions resulting in the production of radiation from the gas

would tend to give a negative current, and, if this negative current were large enough for the electrometer to give an indication, the value of V_2, for which an increasing *positive* current was first obtained, would not give the true correction. It was found, however, in practice, that, for a given value of V_1, the limiting value of V_2, for which a detectable amount of ionisation was produced, was considerably higher than the value of V_2, for which a detectable amount of the first radiation was produced with a suitably adjusted V_3. In other words, more electrons having a velocity slightly in excess of the minimum radiation value, are required to give a detectable radiation current, than are required to give an indication of ionisation when their velocity is slightly in excess of the minimum ionisation velocity. Thus the anticipated difficulty does not arise, since, at the stage when ionisation is detected, the number of electrons concerned is insufficient to give a measurable current due to radiation of the first type. The corrected values of the minimum ionisation velocity, deduced from curves taken under very different conditions of pressure and intensity of electron stream, are in good agreement, the mean corrected value being 16·7 volts. An example of



a curve from which a value has been deduced, together with the corresponding correction curve, is given in fig. 5 (curves I and III). The series of observations represented in this curve were taken at an average pressure of 0·121 mm. From the curve, it is clear that, though the negative current does not actually cease to increase until the point marked Y is reached, the downward slope of the negative current curve begins to get less at the point marked X, so that the latter point is taken as giving the first indication of the beginning of ionisation. The applied accelerating potential difference at the point marked X is 15·05 volts, and, from the correction curve III, it is clear that the correction to be added to this is +1·5 volts, so that the value of the minimum ionisation velocity deduced from this figure is 16·55 volts, which differs very little from the mean of all the accurately determined values.

The curve given in fig. 6 affords interesting confirmation of the value we have deduced for the minimum ionisation velocity by applying the correction obtained in the manner described. In taking the series of observations illustrated in fig. 6, the fields were arranged for the determination of the limiting value of V_2, for which a detectable ionisation current was first produced when V_3 had such a value that all the electrons getting into the space between the gauzes D and N would have an opportunity of acquiring the minimum ionisation velocity. The limiting value of the retarding field, V_2, was ascertained, and V_2 was then reduced 0·2 volt below this limiting



value, so that there could be no doubt that a sufficient number of electrons to give a clear indication of ionisation were being permitted to enter the space between D and N. The accelerating potential difference, V_3, was then gradually increased from a value clearly too low to give the electrons the necessary velocity for the production of ionisation, up to about 18 volts. Under these conditions, the value of V_3, at which an increasing positive current begins, should give the value of the minimum ionisation velocity

independent of correction, except for the 0·2 volt acquired from the fields V_1 and V_2. It will be observed from fig. 6 that the rise in the curve begins when V_3 is 16·6 volts, which gives 16·8 volts as the minimum ionisation velocity, a value in good agreement with the mean value given above.

The Second Radiation Velocity.

The preliminary experiments described in an earlier section of the paper suggested the production of a second type of radiation at an applied potential difference of between 16 volts and 17 volts. This is indicated in both the (I—R) curve and the R curve given in fig. 2. It will be noticed that the indication of this second radiation in the curves falls near the mean value we have given for the minimum ionisation velocity, namely, 16·7 volts. It has also been pointed out that the correction which was found for the first ionisation potential difference is greater than the correction which had to be added to the observed value of the applied potential difference to give the first radiation velocity. The difference between these two corrections in some cases amounted to as much as 0·8 volt. If the correction for the second radiation velocity is the same as that found for the first radiation velocity, the first ionisation point and the second radiation point are actually even closer together than they appear to be from the curves. It therefore seemed desirable to take special series of observations, to investigate whether the first ionisation and the second radiation occur simultaneously.

The type of curve from which most of the accurate values of the second radiation velocity have been deduced was that given by R series of observations. Curves of this type were taken in preference to (I—R) series for the reason given earlier, namely, that (I—R) series did not always give an indication of the second type of radiation. The detection of the beginning of the second radiation therefore depends upon the determination of the point in the R curve, at which the slope increases abruptly. R series of observations for the determination of the second radiation velocity, were taken at average pressures ranging from 0·486 mm. to 0·009 mm., and for different intensities of the electron stream. The values deduced from these curves, and from some (I—R) curves, differed very little from the mean of all the corrected values, namely, 17·8 volts. The special test for the simultaneous occurrence of the first ionisation and the second radiation consisted in taking an (I—R) series of observations for the determination of the first ionisation velocity simultaneously with an R series for the estimation of the second radiation velocity, corresponding points on the two curves being taken consecutively. In the same way, corresponding points on an R correc-

tion curve and on an (I—R) correction curve were taken consecutively. It was thus possible to ascertain with certainty whether the two effects were produced at the same electron velocity or not. An example of such a pair of curves is given in fig. 5. Curves I and III of this figure have already been considered. The curves II and IV are respectively the radiation curve, and the corresponding R correction curve. I and II show clearly that the interval between the applied potential differences at which the first ionisation and the second radiation are first indicated is at least 1 volt. The correction curves III and IV show that radiation and ionisation begin to be detectable for the same value of V_2, namely, when $(V_2-V_1)=1{\cdot}5$ volts, thus giving a positive correction of 1·5 volts for both the radiation and the ionisation. The detection of a radiation current in the R correction curve when $(V_2-V_1) = 1{\cdot}5$ volts does not, however, constitute a proof that this is the correction which has to be added to the applied potential difference at which the bend in the R curve occurs, in order to obtain the second radiation velocity, since it is possible that the observed current in curve IV is due to radiation of the first type.

It has already been pointed out that, when V_3 is only slightly greater than the first radiation velocity, many more electrons are required to give a detectable radiation current than are required to give a detectable ionisation current when V_3 is slightly greater than the first ionisation velocity, *i.e.* (V_2-V_1) must be much smaller in the case of the first radiation than in the case of the first ionisation, for which it is here shown to be 1·5 volts. The radiation current produced by a given number of electrons will, however, increase as the velocity of the electrons increases, so that it is possible that, though with (V_2-V_1) equal to 1·5 volts, the 11·8 volt radiation current is too small to be detected when V_3 is about 12 volts, it may be measurable when V_3 is about 18 volts. This point was tested, by determining for a given pressure and intensity of electron stream, the limiting value of the retarding potential difference, V_2, for which a detectable current was obtained, for different values of V_3, with the electric fields arranged as for an R series. In the particular case tested, it was found that, as V_3 was increased, the limiting value of V_2 at first increased slightly, but soon reached a constant value. This constant value gave a correction of $+1{\cdot}0$ volt. When, however, V_3 had been increased to such a value that the second radiation could be occurring, it was found that the limiting value of V_2 changed abruptly to a value which gave a correction of $+1{\cdot}5$ volts. The correction deduced from the limiting value of V_2 then remained the same as V_3 was further increased. The results of these experiments provide sufficient justification for attributing the negative current, beginning when

(V_2-V_1) was equal to 1·5 volts, to the second type of radiation. The curves of fig. 5 may therefore be taken as showing conclusively that the first ionisation and the second radiation do not occur simultaneously.

In deducing a value of the second radiation velocity from an R curve, such as curve II (fig. 5), the question arises as to whether the amount of the second radiation produced by the number of electrons concerned in first producing a measurable effect in the correction curve IV, would be detectable in the presence of a negative current due to the first type of radiation, when this current is of considerable magnitude. In estimating (from the curves given in fig. 5) the interval between the first ionisation velocity and the second radiation velocity, it seems probable that the points Y and Z are corresponding points, rather than the points X and Z, for it seems improbable that an increase of radiation which would correspond to the ionisation current between the points X and Y in the (I—R) curve would be sufficient to show in the R curve. The interval between the points Y and Z in these curves is 16·75 volts—15·6 volts = 1·15 volts, which gives, as the corrected value of the second radiation point (16·55+1·15 =), 17·7 volts, a value in good agreement with the mean value (17·8 volts) already given. The value 17·8 volts, found in the manner indicated, was confirmed in the same way as the value found for the first ionisation velocity, by taking an (I—R) series of observations with the fields arranged as for the determination of a correction, and with V_2 (the retarding potential difference) adjusted to 0·2 volt less than the limiting value. During these observations, neon was streaming through the apparatus at a low pressure, and it was found that the second type of radiation was able to overcome the first type of ionisation, and to turn the curve down. The accelerating potential difference, V_3, at which the first indication of the second type of radiation was obtained, gave 17·8 volts for the second radiation velocity, thus confirming the value already obtained.

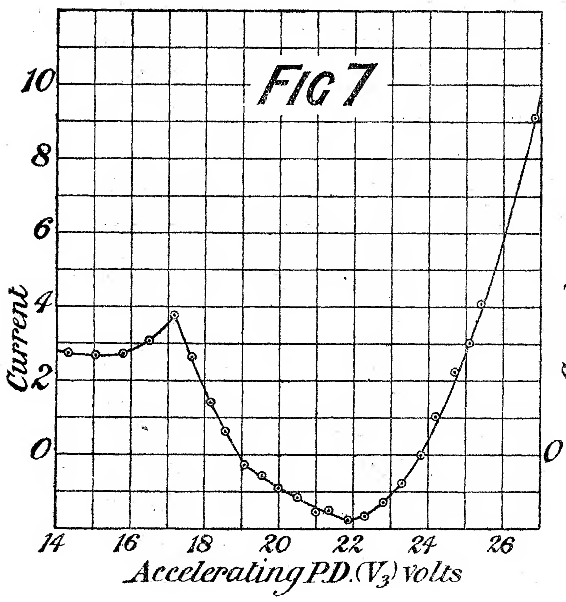
The Second and Third Ionisation Velocities.

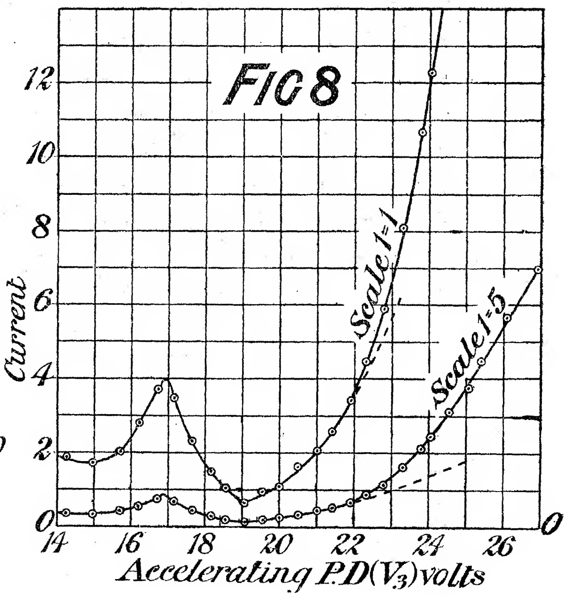
In addition to the ionisation and radiation velocities already investigated in detail, the preliminary experiments indicated the increased production of ionisation at an applied potential difference of about 19 volts, and again at about 22 volts. Of these, the increased ionisation at about 22 volts was much the more marked effect of the two, and in some instances the curves gave no sign of the increase at about 19 volts. Owing to the difficulty of determining jnst where the increase of current begins when this increase has to be detected in the presence of an already considerable current of the same sign, it was decided that the most reliable values for the second and third ionisa-

tion velocities would be obtained if the indication of an increase of ionisation were sought for in the presence of a negative current. It was found that curves of the required type were best obtained by using a smaller electron emission than that employed hitherto, and by having neon streaming slowly through the apparatus, the purifying carbon tube having been strongly heated and pumped immediately before cooling in liquid air and commencing the series of observations. In order to obtain the desired type of curve and the necessary correction under as nearly the same conditions as possible, the (I—R) curves were taken with the potential difference V_2 retarding, instead of accelerating, the electron stream. In the first place, the limiting value of V_2 to give a detectable ionisation current with an (I—R) arrangement of fields was ascertained for different values of the accelerating potential difference V_3, ranging from about 17 volts to 25 volts. No appreciable change in the limiting value of V_2 was found when different values of V_3 were employed, so that the correction for the higher ionisation points cannot be greater than the correction for the first ionisation point. When neon was streaming through at a low pressure it was found that, though the limiting value of V_2 (the retarding potential difference) changed very little as V_3 was given the various different values, yet in some cases the current measured by the electrometer was positive, while in others it was negative. For instance, in one such investigation made for the following three values of V_3, 17·15 volts, 20·0 volts, and 25·5 volts, the limiting value of V_2 was in each case found to be 6·6 volts. With V_3 equal to 17·15 volts, starting with $V_2 = 6{\cdot}6$ volts and gradually reducing it, an increasing positive current was first obtained. This positive current began to decrease with further reduction of V_2 below 5·8 volts, indicating that the difference between 5·8 volts and the limiting value 6·6 volts, *i.e.*, 0·8 volts, added on to 17·15 volts, was sufficient to enable the electrons to give rise to the second type of radiation. When V_3 had the value 20·0 volts, a gradually increasing *negative* current was obtained as V_2 was reduced below 6·6 volts, while in the third case, where V_3 was 25·5 volts, an increasing *positive* current resulted from the same variation in V_2. Since the radiation produced at 17·8 volts is able to overcome the 16·7 volt ionisation, the detection of a positive current for this last value of V_3, even when V_2 had the limiting value, shows that in this case the correction corresponding to this limiting value applies to one of the higher ionisation velocities. Thus, the correction found for the first ionisation velocity can also be used to obtain the higher ionisation points.

In making a determination of one of these higher ionisation velocities, the limiting value of V_2 for which an ionisation current could be detected when V_3 was about 24 volts was first ascertained, and then V_2 was reduced below

this limiting value by 1·0 volt and an (I—R) curve taken by gradually increasing V_3, starting from 14 volts. The reduction of V_2 below the limiting value which lets through the minimum number of electrons necessary to give a detectable current, serves to increase the velocity of this minimum number, and so the correction to be added to the values of V_3 at which indications of increased ionisation were shown in the curve obtained, is thus 1·0 volt. The small electron emission, still further limited by the retarding field V_2, serves to keep the currents measured by the electrometer small, and also tends to prevent the complication introduced by the simultaneous large increase of radiation and of ionisation sometimes observed, which was attributed to neutralisation of the space charge near the filament. Two curves are given below in figs. 7 and 8 which are typical of the results obtained in experiments of this kind, and from which values of the second and third ionisation





velocities can be deduced. During each of these series of observations, the side electrodes G and H were maintained at the same potential as the gauze D, and V_2 was in each case 1·0 volt below the limiting value, so that the correction to be applied to values read from the curves is 1·0 volt. The average pressure during the series of observations represented in fig. 7 was 0·063 mm. This curve shows the first ionisation beginning when V_3 is equal to about 15·7 volts and increasing as V_3 is increased up to about 17 volts, after which it decreases, owing to the production of the second type of radiation. In this curve, when V_3 is increased to 19 volts, the downward slope

of the curve changes and indicates the production of the second type of ionisation. A further change in the curve occurs when V_3 is equal to 21·8 volts, for after this point the negative current rapidly decreases as V_3 is increased and finally gives place to an increasing positive current. In fig. 8 the occurrence of ionisation at 19 volts causes an abrupt upward bend in the curve at this point, and the increase of ionisation at 21·8 volts is shown by the increased slope of the curve after this value is passed. The mean corrected values of the second and third ionisation velocities as deduced from these curves are 20·0 volts and 22·8 volts respectively. The values are in good agreement with the values obtained from a large number of curves, representing observations taken over a range of pressures extending from an average pressure of 0·007 mm. to an average pressure of 0·310 mm. The main differences in the conditions under which the curves in figs. 7 and 8 were taken, were that, in the case of fig. 8, the average pressure was a little higher than in fig. 7 and a rather stronger electron stream was used.

The mean values obtained for the different critical velocities by the detailed experiments described in this section are as follows :—

	Volts.
Minimum radiation velocity	11·8
Second radiation velocity	17·8
Minimum ionisation velocity	16·7
Second ionisation velocity	20·0
Third ionisation velocity	22·8

Previous investigations of the effects of electron collisions with neon have been made by Franck and Hertz,* and by Rentschler.† Franck and Hertz obtained evidence which they interpreted as indicating the occurrence of ionisation at 16 volts, but, as the method they employed did not make it possible to distinguish between ionisation and radiation, their experiments can only be taken as indicating the existence of a critical velocity at this point. Rentschler concluded from his experiments, by the method used by Tate and Foote‡ with metallic vapours, that neon did not show a resonance (or radiation) velocity, and that its ionisation velocity was 19·5 volts. In the course of the present research, the authors carried out several experiments based on the method of Tate and Foote, but found that the resulting curves did not indicate some of the critical velocities which the experiments described in this paper have shown to exist. A discussion of the reasons for

* J. Franck and G. Hertz,' 'Deutsch. Phys. Ges. Verh.,' vol. 15, p. 34 (1913).

† H. C. Rentschler, 'Phys. Rev.,' vol. 14, p. 503 (1919).

‡ J. T. Tate and P. D. Foote, 'Phil. Mag.,' vol. 36, p. 64 (1918).

the failure of this method, when used for gases in which the critical velocities are high, has been given elsewhere.*

Discussion of Results and Conclusion.

The fact that in neon it has been found that there are two critical electron velocities associated with the production of radiation from the gas, and three critical velocities associated with the production of ionisation, all these values being less than 25 volts, suggests that neon differs more in constitution from helium and argon than would be expected from its position in the Table of Elements. It might be suggested that the second radiation velocity, 17·8 volts, and one of the higher ionisation velocities, are analogous to the critical velocities found in helium corresponding to the displacement and to the complete removal, respectively, of the second electron from the atom. In this case, the values referred to above for neon would be either—

(*a*) The electron velocity required to produce further radiation or ionisation respectively from already ionised atoms; or

(*b*) The electron velocity necessary for the production simultaneously of the 16·7 volt ionisation, and additional radiation or ionisation respectively.

Experimental evidence, which makes both of these possibilities seem unlikely, is provided by several series of observations, taken when neon was first entering the apparatus. These series of observations gave curves in which no indication of the critical velocities at 11·8 volts and 16·7 volts was obtained, while those at 17·8 volts and 22·8 volts were plainly shown. It is therefore clear that the effects produced at these higher velocities cannot be dependent upon the presence of positive ions of the kind resulting from the 16·7 volt ionisation. The same experiments constitute an objection to the view that 17·8 volts and 22·8 volts, respectively, correspond to the energies necessary for the production simultaneously of the 16·7 volt ionisation and additional radiation or ionisation, for it is very improbable that the double ionisation of the atom would give a considerable current, when the simple ionisation did not give a measurable effect. On theoretical grounds, the alternative (*b*) is extremely unlikely, since the quantities of energy concerned are so small compared with the quantities required to produce similar effects in helium. Moreover, if (*b*) were the true explanation, the electron velocities required for the displacement and complete removal, respectively, of a second electron from an already ionised atom would be (17·8 − 16·7 =) 1·1 volts and (22·8 − 16·7 =) 6·1 volts, which are lower than the corresponding electron velocities for the normal atom. It does not, therefore, seem possible to reconcile the observed effects with the

* F. Horton and A. C. Davies, 'Phys. Rev.,' vol. 15, p. 498 (1920).

view that, at one of the higher critical ionisation velocities, doubly charged atoms are produced.

The accepted view of the connection between the quantities of energy required for the production of radiation and of ionisation is that they correspond to the first and to the limiting frequency, respectively, of some particular spectral series of the element concerned. On this view, it would be expected that, with every ionisation velocity, there would be associated a definite radiation velocity. In our experiments, evidence of three ionisation velocities and of only two radiation velocities was obtained. It is unlikely that the absence of any indication of a third radiation velocity can be explained by supposing that a third radiation is produced, but is of too small a frequency to give a photo-electric effect, since the three ionisation velocities correspond to frequencies well within the Lyman region of the spectrum. It is possible, however, that two radiation velocities occur so close together that they do not give separate indications in the curves, in which case one of them would escape detection. Whatever view is taken of the origin of the effects occurring at different critical velocities, it seems necessary that a definite radiation velocity should be associated with each ionisation velocity, and it therefore seems probable that, unless one radiation velocity is escaping detection, the ionisation observed at one of the three critical velocities is a spurious effect. The electron velocity, 20·0 volts, at which the second ionisation was detected, is in fair agreement with the value we found for the minimum radiation velocity for electrons in helium (20·4 volts), if allowance is made for the difference in the methods employed in determining the correction in the two cases. If helium were present as an impurity in the neon used, radiation would be produced in the gas when the electron velocity reached 20·4 volts, and this radiation would be of sufficiently high frequency to cause the ionisation of the system to which the ionisation velocity of 16·7 volts is attributable. The radiation produced at 20·4 volts might therefore show, as an increase of ionisation current rather than as an increase of radiation current, and in this case no further change in the ionisation current would be expected when the ionisation velocity of helium (25·6 volts) was reached, since the direct ionisation of this gas by collisions might not result in the production of more positive ions than the indirect ionisation of the neon by the 20·4 volt helium radiation. The presence of helium as an impurity would thus provide a possible explanation for the additional ionisation velocity observed, but, against the adoption of this explanation, must be placed the fact that the neon used had been subjected to a lengthy series of fractionations to purify it from helium, and no trace of this gas could be detected by other means. The explanation

given would, of course, hold equally well if a small proportion of any element having a radiation velocity of about 20 volts were present.

With regard to the two radiation velocities and the ionisation velocities at 16·7 volts and 22·8 volts, experimental evidence makes it appear probable that the radiation velocity 11·8 volts is associated with the ionisation velocity 16·7 volts, and that the radiation velocity 17·8 volts is associated with the ionisation velocity 22·8 volts, for in certain series of observations, already referred to, the 11·8 volt radiation and the 16·7 volt ionisation could not be detected, while the other critical velocities were strongly indicated. On theoretical grounds it is difficult to imagine any other association of these radiation and ionisation velocities, for the ionisation velocity must be higher than the radiation velocity associated with it.

We may, therefore, assume that if neon consists of two or more constituents having different radiation and ionisation velocities, the critical velocities 11·8 volts and 16·7 volts are to be attributed to one constituent, and the critical velocities 17·8 volts and 22·8 volts to another. The positive ray experiments of Sir J. J. Thomson* and the more recent experiments of Dr. Aston† on the mass spectra of the elements have shown that neon contains two constituents of atomic weights 20·00 and 22·00, and possibly a very small proportion of a third constituent, of atomic weight 21·0. A consideration of the arrangement of the elements according to the Periodic Law shows that the existence of *different* elements with these atomic weights is not in accordance with the principle of atomic numbers, and the constituents of neon are considered by Aston to be isotopes. In this case they have the same nuclear charge and the same number of surrounding electrons, which might be expected to be distributed in the same way about the nucleus in each case. On this view it is difficult to see how the presence of two or more isotopes can account for the existence of two radiation velocities and three ionisation velocities. If neon consists of a mixture of two or three different elements of the same group, one having an ionisation potential difference of 16·7 volts and another having an ionisation potential difference of 22·8 volts, the spectrum of the gas should show some lines when excited by electrons having a velocity of 22·8 volts or more, which would be absent when the velocity of the exciting electrons was less than this. Attempts were made to detect differences in the visible spectrum when electron velocities above and below this limit were used, but the experiments showed that, in order to obtain conclusive evidence on this point, a specially designed arrangement for the

* J. J. Thomson, 'Rays of Positive Electricity,' p. 112 (1913).

† F. W. Aston, 'Phil. Mag.,' vol. 39, p. 449 (1920).

concentration of the luminosity would be required. The authors hope to investigate the matter further.

The spectrum of neon, excited in the usual way, has been examined in considerable detail by various investigators. More recently, Paschen* and Hicks† have independently carried out researches upon the classification and arrangement of the lines observed. Hicks finds that neon gives results analogous to those obtained with the other inert gases, except that it differs from these in not showing two different spectra according as the discharge is passed with or without a condenser in the circuit.‡ The neon spectrum is compounded of the red and blue spectra typical of the rare gases, the blue spectrum being completely analogous to the blue spectra of the other gases. In the red region, however, there appears to be an excess of red lines over the number to be expected from the atomic weight of neon and its position with respect to the other elements of the same group. Hicks finds parallel D, S, and F series in neon, which are all related by the linkages to be expected and by Watson's constant frequency differences. The separations and linkages to be expected for any element are dependent upon a constant, known as the oun, characteristic of the element, and accurately proportional to the square of its atomic weight. It would, therefore, seem that if neon contains either two isotopes or two separate elements of atomic weights 20 and 22, two sets of linkages would be obtained, giving different values of the oun. Hicks' classification of the lines and his calculation of the neon oun show no evidence of this and thus throw no light on the origin of the several critical velocities we have obtained.

Paschen found it possible to group nearly all the observed lines into series of the forms:—

1	$1{\cdot}5,\ \mathrm{S}_n - m,\ \mathrm{P}_{n'}$
2	$2,\ \mathrm{P}_n - m,\ \mathrm{D}_{n'}$
3	$2,\ \mathrm{P}_n - m,\ \mathrm{S}_{n'}$

Some of these follow the Ritz interpolation formula with great exactitude while others require a modification of the Ritz expression. The series of the type $1{\cdot}5,\ \mathrm{S}_n - m,\ \mathrm{P}_{n'}$ were found to tend towards limiting frequencies for which the corresponding potential differences, calculated from the relation $e\mathrm{V} = hn$, were very nearly the same. These limits were not directly observed, but as most of the lines in the series fell within the measured part of the

* F. Paschen, 'Ann. der Physik,' vol. 60, p. 405 (1919).

† W. H. Hicks, 'Phil. Trans.,' A, vol. 220, p. 335 (1920).

‡ This is not in agreement with the results of Merton who found that neon resembled the other inert gases in this respect. T. R. Merton, 'Roy. Soc. Proc.,' A, vol. 89, p. 447 (1914).

spectrum, the values of the constants of the series could be ascertained from directly observed lines. One of the series which agreed accurately with the Ritz formula contained the expression (m, S_5). From this series the value of S_5 was obtained and the limit (1·5, S_5) of some of the series of the (1·5, $S_n - m$, P) type was calculated. This limit was 39,887·610 ± 0·05, and the corresponding potential difference is equal to 4·92 volts. On the accepted view, a radiation and the corresponding ionisation are connected with the excitation of the first and last lines, respectively, of the particular series resulting from displacements of an electron from its normal orbit. There must, therefore, be a series corresponding to displacements starting from the first orbit to which an electron can be projected from the normal orbit. The limiting frequency of this series would be expected to correspond to the difference between the minimum ionisation potential difference and the minimum radiation potential difference, which was found in the present research to be (16·7 − 11·8 =) 4·9 volts. Paschen's results show that the spectrum of neon contains series having limiting frequencies corresponding to this potential difference. Thus, although there is no evidence available for the region of the spectrum which includes the frequencies calculated from the observed critical electron velocities, the existing spectroscopic evidence is in accord with the values we have obtained for the minimum radiation and minimum ionisation velocities. The interval between the second radiation velocity and the third ionisation velocity is equal to (22·8 − 17·8 =) 5·0 volts, which again agrees, within the limits of experimental error, with the potential difference corresponding to the limit of known series in the neon spectrum.